

Environmental impact analysis of laser cutting: A case study of thin stainless steel and aluminum alloy sheets

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ABSTRACT

The analysis of environmental impacts of manufacturing processes is essential for promoting cleaner and more sustainable production. The present study examined the total environmental impact in laser cutting of thin stainless steel and aluminum alloy sheets. To this aim, an integrated approach, which combines design of experiments methodology for parameter effect assessment, analytical-empirical models and life cycle assessment methods for resource consumption estimation and environmental impact evaluation, was proposed. In addition to the analysis of main laser cutting parameter effects on total environmental impact, development of regression models for predicting environmental impact, and analysis of contributions to the environmental impact, i.e., energy consumption of the laser cutting machine, assist gas consumption, and generated waste material, were also addressed. The presented approach is useful and receptive in order to quantify and predict the environmental impact of the selected laser cutting conditions directly during the process planning step.

KEYWORDS

Laser Fusion Cutting, Sustainability, Cleaner Production, Life Cycle Assessment.

1. INTRODUCTION

Alongside conventional, non-conventional technologies are being increasingly adopted in modern sheet-metal manufacturing [1]. Laser cutting technology, in particular, is widely used for contour cutting due to many advantages that bring multiple cost, quality, and efficiency benefits. Although laser cutting is a well-established technology, achieving superior performance in terms of quality, cost, and productivity remains challenging due to the complex and often nonlinear interactions among process parameters [2]. In addition, integration of an increasing number of performances is essential to maintain industrial competitiveness [3]. Therefore, process modelling is necessary to explain process behaviour, parameter effects, and their interactions, enabling effective process planning and optimization of the process. Given its complex multi-input, multi-output nature, laser cutting technology has been extensively studied with respect to various performance measures over many years. Numerous authors have recently addressed the analysis, modelling and optimization of quality characteristics, including kerf width [4,5], kerf deviation [6], kerf taper [7], surface roughness [8], dross formation [9], heat-affected zone [10], dimensional and shape accuracy [11], striations [12], microhardness [13], residual stresses [14], recast layer [15], surface morphology [16], etc.

Several studies have addressed the economic aspects [17-19], approaches for nesting and laser cutting path optimization [20-23], as well as productivity analysis of the process [24-26]. Because material processing technologies involve substantial consumption of energy, materials, and resources, the adoption of cleaner production and the promotion of environmental sustainability are essential [27]. Therefore, some studies have addressed sustainability aspects in laser cutting [28-35]. Although in comparison to conventional cutting technologies, laser cutting technology is more environmentally friendly [36], increasing awareness for sustainability highlights the importance of saving energy and material resources, reducing waste generation and minimizing environmental burden [33]. Therefore, the goal of the present study is the analysis of the effects of laser cutting parameters, which are critical to process planning, on the total environmental impact in laser cutting of thin stainless steel and aluminum alloy sheets. To this end, an integrated approach, based on

consideration of laser cutting parameter recommendation guidelines, application of design of experiments methodology and application of analytical and empirical models for resource consumption, as well as life cycle assessment (LCA) method, was developed. In addition to the analysis of main parameter effects on total environmental impact, development of regression models for predicting environmental impact, and analysis of contributions to the environmental impact, i.e., energy consumption of the laser cutting machine, assist gas consumption, and generated waste material, were also addressed.

2. APPLIED METHODOLOGY

The environmental impact of laser cutting was evaluated using the Eco-indicator 99 endpoint method [37]. It is a life cycle impact assessment (LCIA) method that aggregates environmental damage to human health, ecosystem quality, and resource depletion into a single environmental score expressed in eco-indicator points (mPts). Actually, LCA methods are the primary approach used to evaluate the environmental impacts of material cutting technologies [33].

A gate-to-gate system boundary was defined for a laser cutting operation of a high-power (4 kW) conventional CO₂ laser cutting machine (Prima Power Domino Evoluzione). Laser nitrogen cutting of stainless-steel sheet with a thickness of 1 mm was considered, while analysing energy consumption of the laser cutting machine, assist gas consumption during the process, and waste material. Process emissions and other consumables were found to have a negligible contribution [38] and were therefore excluded from the analysis.

In the estimation of these quantities, four process parameters, i.e., laser power, assist gas pressure, cutting speed and nozzle diameter, were considered. These parameters predominantly affect required laser cutting machine power for different laser output levels, assist gas consumption, melt volume and material waste generation and cycle time, which are the dominant contributors to the Eco-indicator 99 environmental impact of laser cutting. The estimation of these quantities was based on data and available models from referential literature [17,35,37-39].

In order to systematically analyse the effects of laser power, assist gas pressure, cutting speed and nozzle diameter on environmental impact, a full factorial experimental design was adopted. The levels of the input variables were determined by considering the industrial CO₂ laser cutting parameter recommendation guidelines [40]. For each laser experimental trial, i.e., a combination of laser cutting parameter values, one can calculate the contributions related to the energy consumption of the laser cutting machine, assist gas consumption during the process, and waste material. Ultimately, one can determine EI-99 single scores per unit cut length (mPts/m). The applied methodology for assessing the environmental impact in laser cutting of stainless steel and aluminum alloy sheets is given in Figure 1.

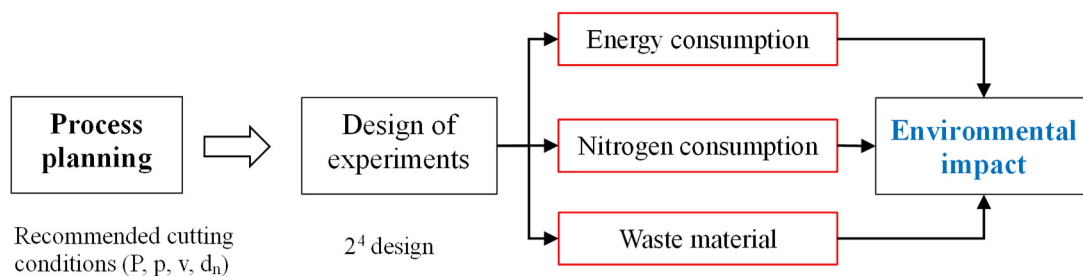


Figure 1: Applied approach for assessing the environmental impact in laser cutting

3. ANALYSIS OF RESULTS

The experimental results were analysed using standard procedures from the design of experiments methodology [41]. Main effects and interaction effects were evaluated using factorial analysis, and the significance of model terms was assessed based on their percentage contribution, calculated from the corresponding mean squares. Estimated parameter effects of laser power (P), nitrogen pressure (p), cutting speed (v) and nozzle diameter (d_n) on output (eco-indicator points per unit cut length) are given in Figure 2.

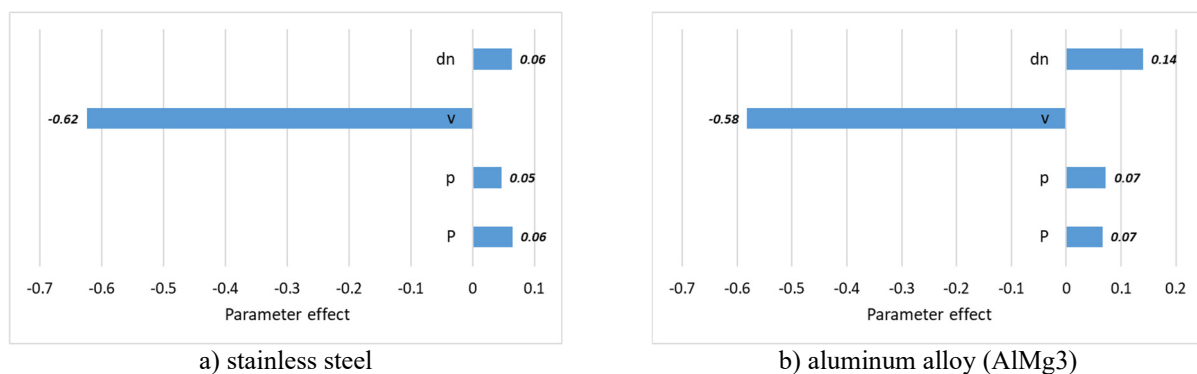


Figure 2: Estimated parameter effects on total environmental impact

As can be observed from Figure 2, cutting speed exhibits the greatest influence, indicating that environmental impact in laser nitrogen cutting of stainless steel and aluminum alloy sheets with a thickness of 1 mm is primarily governed by energy consumption per unit cut length. Nozzle diameter, laser power, and nitrogen pressure show very limited effects. While all main effects were statistically significant, all two-factor interactions were estimated to be negligible, except for the nozzle diameter and nitrogen pressure two-factorial interaction, which showed a nearly statistically significant contribution. While this suggests that the environmental impact of the laser cutting process is largely dominated by main effects, it should be noted that parameter interactions may significantly impact kerf geometry. In the present case, however, the kerf width was estimated using a simplified model that only considers sheet thickness. Laser power, nitrogen pressure, and nozzle diameter positively correlate with output, reflecting slight increases in environmental impact when these parameters are increased. On the other hand, cutting speed exhibits the strongest negative correlation, indicating that increasing cutting speed reduces the environmental impact.

Based on estimated by the output average and main effects of the considered laser cutting parameters, the regression model for predicting environmental impact (in mPts/m) in laser cutting of stainless steel and aluminum alloy can be written as:

$$EI_{score(stainless\ steel)} = 3.94 + 0.032 \cdot x_1 + 0.023 \cdot x_2 - 0.312 \cdot x_3 + 0.032 \cdot x_4 \quad (1)$$

$$EI_{score(aluminum\ alloy)} = 3.12 + 0.033 \cdot x_1 + 0.036 \cdot x_2 - 0.291 \cdot x_3 + 0.07 \cdot x_4 \quad (2)$$

where the coded variables x_1 , x_2 , x_3 and x_4 represent laser power (P), nitrogen pressure (p), cutting speed (v) and nozzle diameter (d_n), respectively.

The obtained linear regression models predict the Eco-indicator 99 score as a function of laser cutting parameters. They can be used to estimate environmental impact for arbitrarily chosen laser cutting conditions, though within the studied range. In addition, they enable single and multi-objective process optimization when integrated with cost, productivity, or quality models.

The laser cutting conditions that minimize environmental impact can be easily identified. These conditions correspond to a combination of low laser power, high cutting speed, low nitrogen pressure, and small-diameter nozzles. Within experimental design points, minimal environmental impact is estimated to be 3.94 mPts/m for cutting stainless steel and 2.72 mPts/m in the case of cutting aluminum alloy. On the other hand, laser cutting conditions in which the highest amounts of energy and materials are being consumed result in an environmental impact of 4.35 mPts/m for stainless steel cutting and 3.58 mPts/m in the case of aluminum alloy. The estimated mean environmental impact for the entire experiment is 3.94 mPts/m for stainless steel cutting, while in the case of cutting aluminum alloy is 3.12 mPts/m, which is a reduction of about 20%. The lower environmental impact of the aluminum alloy is primarily due to the higher achievable cutting speed, which reduces the energy consumption per meter of cut.

It should be noted that the selection of laser cutting parameter combinations that minimize environmental impact must be done carefully and validated to ensure process quality. For instance, parameters should be verified by calculating severance energy to ensure sufficient energy input for full sheet penetration and reliable cuts with acceptable/required cut quality. This ensures that improvements in sustainability are not achieved at the expense of cutting quality performance.

The different contributions to the environmental impact, i.e., energy consumption of the laser cutting machine, assist gas consumption during the process, and waste material, are given in Figure 3. As can be seen, energy consumption by the laser cutting machine has the highest share in the total environmental impact of the laser cutting process. Due to the higher required gas flow and greater energy density for laser cutting of aluminum alloy, the relative contributions of energy consumption, nitrogen consumption, and waste material are somewhat different than those in the case of stainless steel. It should be noted that the relative contributions of energy consumption, nitrogen consumption, and waste material are not fixed and may change to a certain extent. In particular, increased gas flow requirements and higher energy power densities associated with cutting thicker sheets can alter the balance between these contributions.

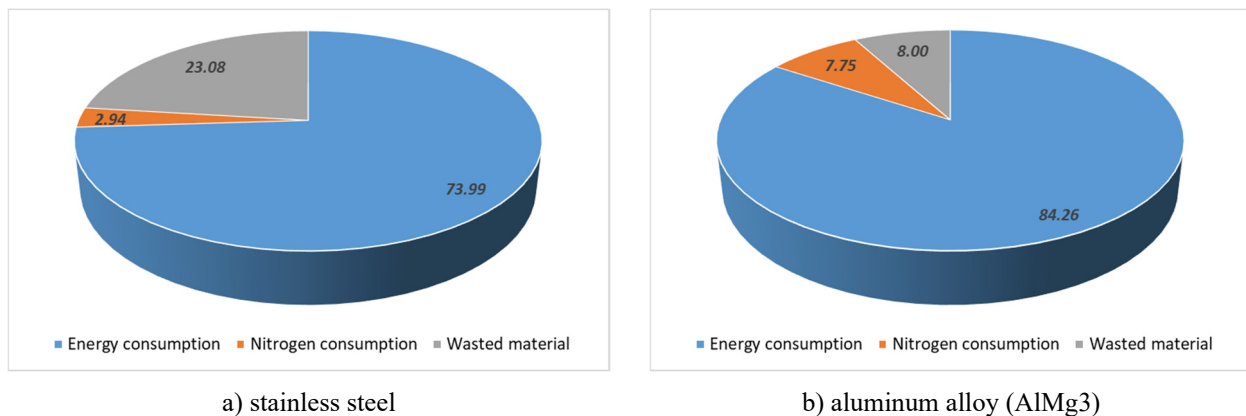


Figure 3: Percentage contributions to environmental impact

The total environmental impact of one hour of productive operation using a 4 kW CO₂ laser cutting machine to cut 1 mm thick stainless steel was estimated to be 1640 mPts. This estimate, together with the trends observed in the previous analysis, is well aligned with the findings of Duflou et al. [35], who reported a total environmental impact of 1756 mPts for one hour of CO₂ laser cutting of mild steel St37-2. In that study, energy consumption accounted for approximately 66% of the total impact, followed by material waste (23%) and process gas consumption (11%), which is consistent with the dominance of energy consumption observed in the present study. Duflou et al. [34] further reported that a proper selection of the laser cutting machine, selective activation and deactivation of non-required subsystems during both productive and non-productive modes, as well as nesting optimization, can lead to tangible savings in material consumption and associated environmental impacts.

4. CONCLUSION

The present study focused on the analysis of energy consumption, assist gas consumption and generated waste material, which altogether contribute to the environmental impact in laser cutting of thin stainless steel and aluminum alloy sheets. An integrated approach, which combines the design of experiments methodology for parameter effect assessment and analytical-empirical models and LCA methods for resource consumption estimation and environmental impact evaluation, was proposed. Based on the conducted analyses, there are several main conclusions:

- Laser cutting of thin aluminum alloy sheets is more environmentally friendly, in comparison to stainless steel cutting, and this can be attributed to lower energy requirements and associated impacts per meter of cut.
- The environmental impact of both materials is strongly controlled by cutting speed.
- Process optimization for environmental performance should prioritize cutting speed, followed by nozzle diameter and laser power. It should be noted, however, that the effect of given main laser cutting parameter changes with regard to the choice of the material type, and it also changes with the change in sheet thickness, with the expectation that with an increase in sheet thickness, the effect of nozzle diameter would be pronounced.
- The absolute share of the resource consumption for both materials is similar, although due to different required gas flow, energy density levels and physical properties, relative contributions are somewhat different.
- The derived prediction models can serve as a guideline for evaluating the environmental impact of arbitrarily chosen laser cutting regimes.
- It should be noted that the obtained results may vary, given the variation intervals for the main laser cutting parameter levels, which were in the present study taken following industrial recommendations.

The presented approach is useful and receptive in order to quantify and predict the environmental impact of the selected laser cutting conditions directly during the process planning step. One limitation of the present study is that kerf width was assumed to be a function of only sheet thickness and was assumed to be the same for both materials under the same cutting conditions.

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